Basin-scale water-balance estimates of terrestrial water-storage variations: Potential for data assimilation

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1. Introduction

Terrestrial water storage (mostly encompassing soil moisture, groundwater and snow) is a key climatic variable, which is relevant both for short-term and seasonal forecasting, as well as for long-term climate modeling. Despite its importance, it is not routinely measured and observations of its individual components are scarce. A possible approach for deriving estimates of this quantity is the use of water-balance computations based on the following three variables: moisture flux convergence, changes in atmospheric moisture content, and river runoff (Seneviratne et al. 2004, hereafter referred to as S04). This methodology was shown to give reliable results for various river basins of the northern mid-latitudes and to compare well with available ground observations (S04; Hirschi et al. 2004, hereafter referred to as H04). Here we compare estimates derived with this approach with offline simulations performed with the National Aeronautics and Space Administration (NASA) Catchment Land Surface Model (hereafter "Catchment model" or CLSM; Koster et al. 2000; Ducharne et al. 2000). These results are used to assess the potential gain in using water-balance estimates of terrestrial water-storage variations in a data assimilation framework.

2. Employed data

2.1 Water-balance estimates of changes in terrestrial water storage

The present study makes use of estimates of basin-scale terrestrial water-storage variations (S04, H04), derived with the following equation (e.g. Peixoto and Oort 1992):

$$\left\{\overline{\frac{\partial S}{\partial t}}\right\} = -\left\{\overline{\nabla_H \cdot \mathbf{Q}}\right\} - \left\{\overline{\frac{\partial W}{\partial t}}\right\} - \left\{\overline{R}\right\} \tag{1}$$

where $\left\{\overline{\nabla_H \cdot \mathbf{Q}}\right\}$ is the moisture flux divergence, $\left\{\overline{\frac{\partial W}{\partial t}}\right\}$ is the change in atmospheric moisture content in the column above the considered area, and $\left\{\overline{R}\right\}$ is the measured runoff. All quantities are temporal and areal averages for a given time frame (monthly variations) and region. Note that the area of the considered domain is a critical factor for the accuracy of such computations and should be of the order of 10^5 to 10^6 km^2 at least (e.g. Rasmusson 1968, Yeh et al. 1998). S04 tested this approach in a 10-year (1987-1996) case study for the Mississippi River basin using European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-40 reanalysis data and streamflow measurements. The derived estimates were found to be reasonable for all Mississippi subbasins and to agree well with available observations of soil moisture, groundwater and snow in Illinois. The dataset used here was derived for several river basins of the northern mid-latitudes and covers the whole ERA-40 period (1958-2002, see H04). For the present study, we only use data from river basins with soil moisture observations (Amur, Dnepr, Don, Lena, Neva, Ob, Volga, Yenisei, see Figure 1a). The comparisons also include the Illinois domain (Figure 1b) investigated in S04.

2.2 Catchment Model integrations

The land surface integrations analyzed here were performed with the Catchment model (Koster et al. 2000, Ducharne et al. 2000), a recently developed land surface scheme, which uses the hydrological catchment (or watershed) as basic computational unit. In each catchment, the vertical profile of soil moisture is determined by the equilibrium soil moisture profile from the surface to the water table, and the deviations from the equilibrium soil moisture profile in a 1-m root zone layer and a 2-cm surface layer. Unlike traditional, layer-based models, the Catchment model includes horizontal redistribution of soil water within each hydrological catchment based on the statistics of the catchment topography (Koster et al. 2000). The present simulations, covering a 15-year period (1979-1993), are forced with a dataset combining ERA-15 reanalysis data with observations-based corrections for precipitation, radiation, temperature, and humidity (Berg et al. 2003). These integrations were conducted and analyzed by Reichle et al. (2004) in a recent study comparing satellite and model soil moisture with ground observations.

2.3 Ground observations

Soil moisture measurements from the Global Soil Moisture Data Bank (Robock et al. 2000) are available for various basins in Russia and Asia (Amur, Dnepr, Don, Lena, Neva, Ob, Volga, Yenisei; Figure 1a) as well as for 19 sites in the state of Illinois (Hollinger and Isard 1994, Figure 1b). For Illinois, concomitant groundwater (Figure 1b) and snow measurements (not shown) are also available from the Illinois State Water Survey and the Midwest Climate Center, respectively (e.g. Yeh et al. 1998, S04). For the present comparisons, areal estimates for the investigated domains are obtained through an averaging of the available observations for the respective basins or domains. Note that in some regions this procedure can lead to some biases if the observations are not well distributed throughout the considered domain.

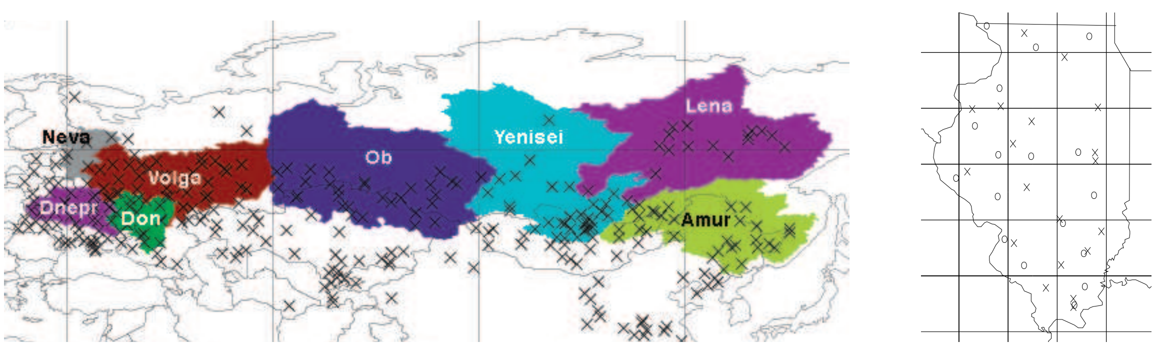

Figure 1: (a) Basins investigated in Asia and soil moisture stations available (crosses); (b) Soil moisture (crosses) and groundwater (circles) measurements sites available in Illinois.

3. Results

First, we compare the respective correlations of the water-balance estimates and the model integrations with the ground observations. Figure 2. displays the coefficients of correlation (r^2) of the two datasets in each investigated domain for the years with available observations witin the time period 1979-1993, both for the absolute values (top) and the anomalies (bottom). Note that in the case of the Catchment model, we use the total terrestrial water storage of the model (i.e. including soil water down to the water table, as well as snow and interception) for consistency with the water-balance estimates. One should keep in mind that the observations, with the exception of Illinois, correspond for their part to variations in soil moisture only.

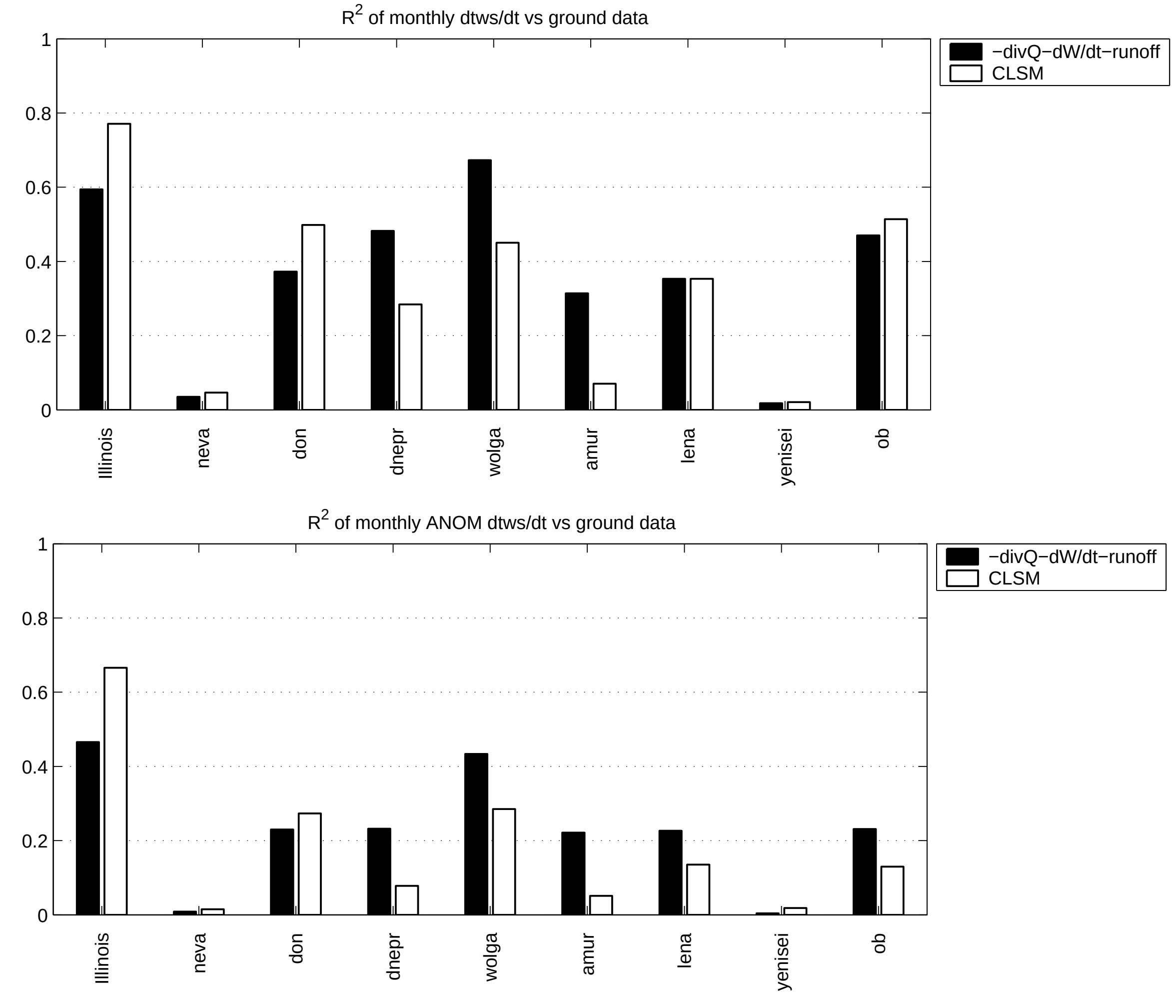

Figure 2: Histograms of r^2 values between the ground observations and the water-balance estimates (black), respectively the Catchment model (white): (top) Absolute values; (bottom) anomalies.

The agreement between the two datasets and the observations varies from region to region, but the two approaches perform worst in the same domains (Yenisei, Neva). Note that this might be due in part to poor representability (Neva) or uneven distribution (Yenisei) of the available observations in these two basins. In the other domains, the water-balance estimates and the land surface model appear similarly skillful on average, though significant differences are found in some domains (Illinois, Dnepr, Volga, Amur). In Illinois, the Catchment model is closer to the observations, possibly due to a high quality of the forcing data in this region. In the Amur basin, on the contrary, the model performs comparatively poorly, either due to poorer forcing or to model biases in this region. Note that rain gauge density is known to be a critical factor for the accurate forcing of a land surface model (Oki et al. 1999), and is likely to be only sufficient in North America and Europe (Koster et al. 2004, Reichle et al. 2004).

Interestingly, the water-balance estimates appear comparatively skillful at capturing the interannual variability of the observations (Figure 2, bottom plot). This can be mostly linked to the contribution of the moisture flux convergence, as this component correlates best with the anomalies of the observed variations in terrestrial water storage and soil moisture (Figure 3).

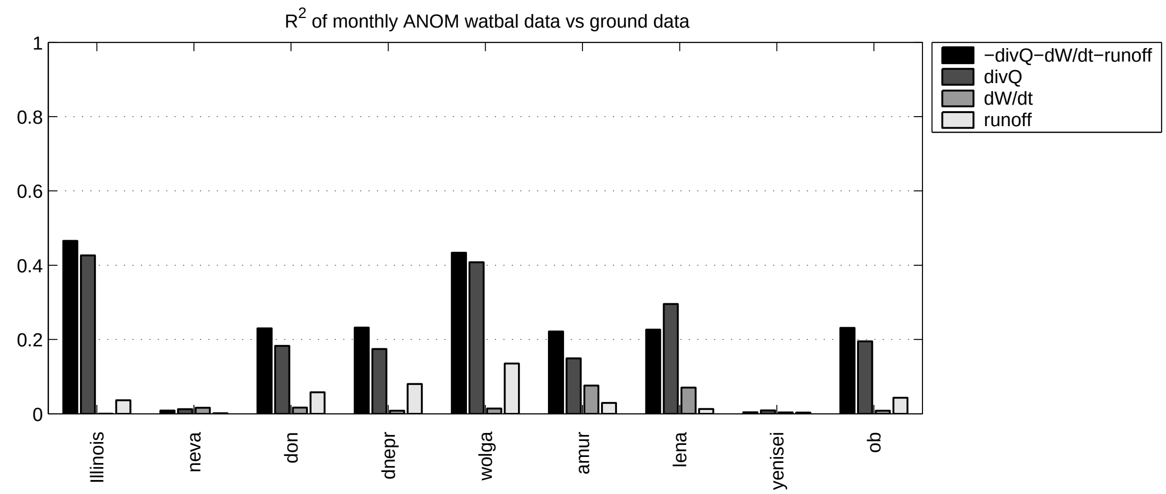

Figure 3: Histogram of r^2 values between ground observations and individual components of water-balance estimates: sum of components (black), moisture flux divergence (dark gray), changes in atmospheric moisture content (medium gray), and runoff (light gray): Anomalies.

4. Conclusions

Preliminary results suggest that both the water-balance estimates and the land surface model driven with optimized forcing are similarly skillful on average, but that their performances can significantly differ in some regions, possibly dependant on the quality of the precipitation forcing used to drive the land surface model. Their skill appears in part complementary: They perform best in different regions (Illinois for the land surface model and Northern Russia for the water-balance estimates), and also capture different features from the observations, the water-balance estimates being more skillful at capturing the interannual variability of the observations. This suggests that quantities such as atmospheric moisture convergence or runoff could possibly be used with success in a data assimilation framework aiming at the creation of a terrestrial water-storage dataset. The potential of such an approach is expected to be highest in regions with poor forcing data.

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